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NEUTRAL BEAM DEVELOPMENT AT BNL

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The long-term objective of the BNL Neutral Beam Development Group is to design and test a neutral beam system, using negative ion sources with a high beam current density. The principal elements of such a system are: a source of negative ions, beam extraction and transport system, accelerator, neutralizer, and the system for the removal and dumping (or energy recovery) of the remaining charged components of the beam. In the past year, a transition has been made from high current density, but pulsed, negative ion sources to sources designed to operate stedy state. Two variants of the basic magnetron source geometry are being studied: the standard one with the discharge established in the interelectrode gap and the other with plasma injection from a hollow cathode discharge (HCD). Both sources have so far operated with steady state discharges. To date 0.11 A of H^- ion current has been extracted from the standard version, while about 1 A of H^- ions has been produced on a surface, transported through the plasma and collected on a separate electrode in the HCD system. If the standard magnetron will be the source of choice, the plan is to transport the beam from a 2 A source unit around a bending magnet, followed by dc acceleration of the beam to 200 keV. These units would be stacked to obtain higher total currents. The source with plasma injection is expected to operate at much lower pressures (10^{-4} to 10^{-3} Torr) and therefore closed coupled acceleration of the beam to 200 KeV may be envisioned. This approach leads to a considerably more compact system. For energies above 200 keV, MEQALAC, dc acceleration with periodic electrostatic adrupole focusing, and the RFQ are being

II. Ion Sources

In BNL ion sources negative ions are produced by the interactions between particles diffusing out of a plasma (density 10^{13} to 10^{14} cm^{-3}) and a negatively biased, low work function surface. The program was initially aimed at producing high current, high current density beams, but in a pulsed mode. By 1976, 1A of H^- ions was produced in 10 ms pulses from an uncooled standard magnetron source. It was a substantial improvement in the magnetron geometry, achieved in 1979[1], that led to the design of a steady state magnetron: it consisted of the widening of the back part of the discharge gap and of the introduction of geometrical focusing of fast negative ions from the cathode into the extraction slits. In this way, a steady state operating magnetron source could be designed using simple water flow to cool the electrodes.[2] This source, Mk V model, was fabricated[3] in 1980 and put into operation in 1981. Figure 1 shows its cross section; cooling channels are visible in all the electrodes. With a cathode surface area of 60 cm^2 and a maximum cathode power density of 0.2 kW/cm^2, it should deliver 1-2 A of H^- or D^- ions. For initial source testing, extractor was solid (no cooling) and its voltage pulsed (1s, 0.1 Hz), while the discharge was running steady state. During initial tests the source has operated about 200 hours with the discharge, at input power levels up to 7.5 kW.[4] At reduced power levels, 0.11 A of H^- ions were extracted through a 2 cm^2 aperture. The main problem seems to be the proper control of cesium density in the source and experiments are under way to use pressurized hot water (≈ 100° C) for electrode cooling.

injection from a hollow cathode discharge (HCD). Both sources have so far operated with steady state discharges. To date 0.11 A of H^- ion current has been extracted from the standard version, while about 1 A of H^- ions has been produced on a surface, transported through the plasma and collected on a separate electrode in the HCD system. If the standard magnetron will be the source of choice, the plan is to transport the beam from a 2 A source unit around a bending magnet, followed by dc acceleration of the beam to 200 keV. These units would be stacked to obtain higher total currents. The source with plasma injection is expected to operate at much lower pressures (10^{-4} to 10^{-3} Torr) and therefore closed coupled acceleration of the beam to 200 KeV may be envisioned. This approach leads to a considerably more compact system. For energies above 200 keV, MEQALAC, dc acceleration with periodic electrostatic quadrupole focusing, and the RFQ are being considered. Further downstream in the neutral beam line, a novel type of the plasma neutralizer is being considered, which uses several HCD's to feed a plasma into a longitudinal solenoidal magnetic field. Presently, there is very little work being done on the last element of the beam line, system for removal and dumping of charged components.

I. Introduction

Since 1974, BNL group has been involved in the development of high current negative ion sources for use in high power efficiency neutral beam lines. A common feature of all BNL sources is the surface-plasma method of negative ion production, with high converter current density (primary current density: 1-2 A/cm^2; emitted H^- or D^- current density $>$ 0.1 A/cm^2), resulting in compact source modules. The design and performance of the two source concepts will be discussed in Section II. The progress in the studies of the extraction, transport and acceleration of negative ions will be described in Section III, while Section IV will cover the concept for a plasma neutralizer with more than 80% neutralization efficiency. Finally, Section V will address the incorporation of the two source approaches into a 10 A, 200 keV D^- "proof-of-principle" beam line.

this way, a steady state operating magnetron source could be designed using simple water flow to cool the electrodes.[2] This source, Mk V model, was fabricated[3] in 1980 and put into operation in 1981. Figure 1 shows its cross section; cooling channels are visible in all the electrodes. With a cathode surface area of 60 cm^2 and a maximum cathode power density of 0.2 kW/cm^2, it should deliver 1-2 A of H^- or D^- ions. For initial source testing, extractor was solid (no cooling) and its voltage pulsed (1s, 0.1 Hz), while the discharge was running steady state. During initial tests the source has operated about 200 hours with the discharge, at input power levels up to 7.5 kW.[4] At reduced power levels, 0.11 A of H^- ions were extracted through a 2 cm^2 aperture. The main problem seems to be the proper control of cesium density in the source and experiments are under way to use pressurized hot water (≈ 100° C) for electrode cooling.

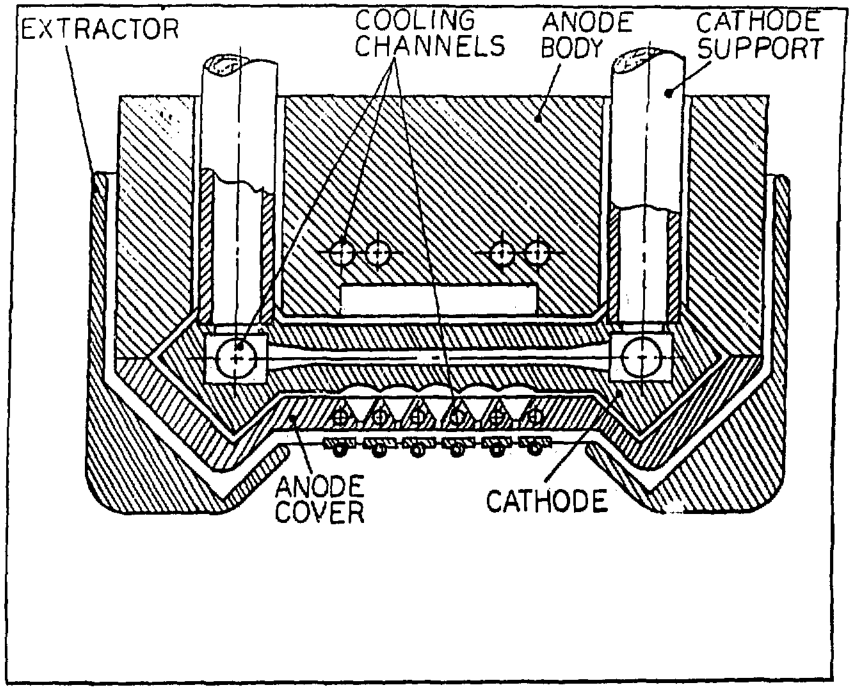

Fig. 1. Cross section of the Mk V cooled magnetron source.

The best gas efficiency achieved with standard BNL magnetron sources is still a relatively low 6%. Hollow cathode discharges offer a source of almost fully ionized gas and this approach has been pursued at BNL since 1979. Plasma densities up to 10^{14} cm^{-3}

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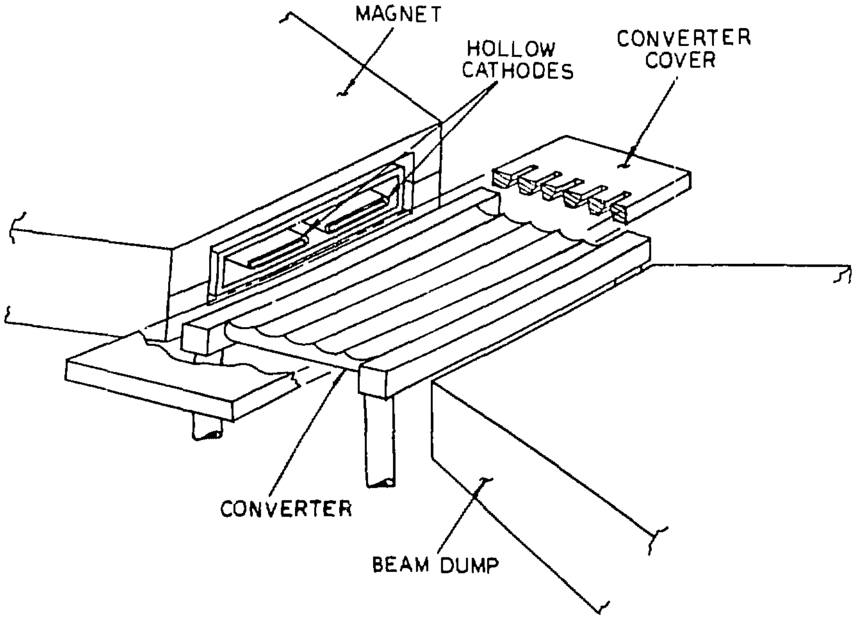
can be achieved at background pressures of 10^{-4} to 10^{-3} Torr, which suffices for negative ion source applications. Initial feasibility experiments[5] have been done on an HCD test stand at MIT, where 1 A/cm^2 of steady state positive ion current was drawn onto a negatively biased, 3 cm^2 molybdenum converter. When cesium was deposited on the converter surface, the current density increased to 2.7 A/cm^2 and it is estimated that at least 0.3 A/cm^2 of H^- ions was produced on the converter and transported through the plasma to a grounded collector electrode. In subsequent experiments at BNL, single and double hollow cathodes with rectangular cross sections have been operated steady state.[6] Initial tests are in progress with a larger structure, incorporating two hollow cathodes delivering a total plasma current of 100 A, and a converter electrode (5 cm x 5 cm). Figure 2 shows the sketch of the structure; all electrodes are water cooled, except the extractor, which is solid and operates in the pulsed mode. Steady state operation of the two cathodes has been achieved, at pressures below 10^{-3} Torr. It is expected that such a source should deliver 1-2A of H^- or D^- ions in steady state, with a gas efficiency approaching 50%.



that it is possible to achieve 80% transmission efficiency (from 0.5 A at the entrance the beam was reduced to 0.4 A at the exit) with a substantially reduced divergence. Such a bending magnet serves a multiple purpose: gas flowing out of the source is pumped away before the accelerator, transported beam consists of H^- ions only, a better emittance match becomes possible, and the source is protected from particle bombardment. Figure 3 shows a possible configuration for the magnetic dipole transport and subsequent dc acceleration of a 1-2A beam from the Mk V magnetron.

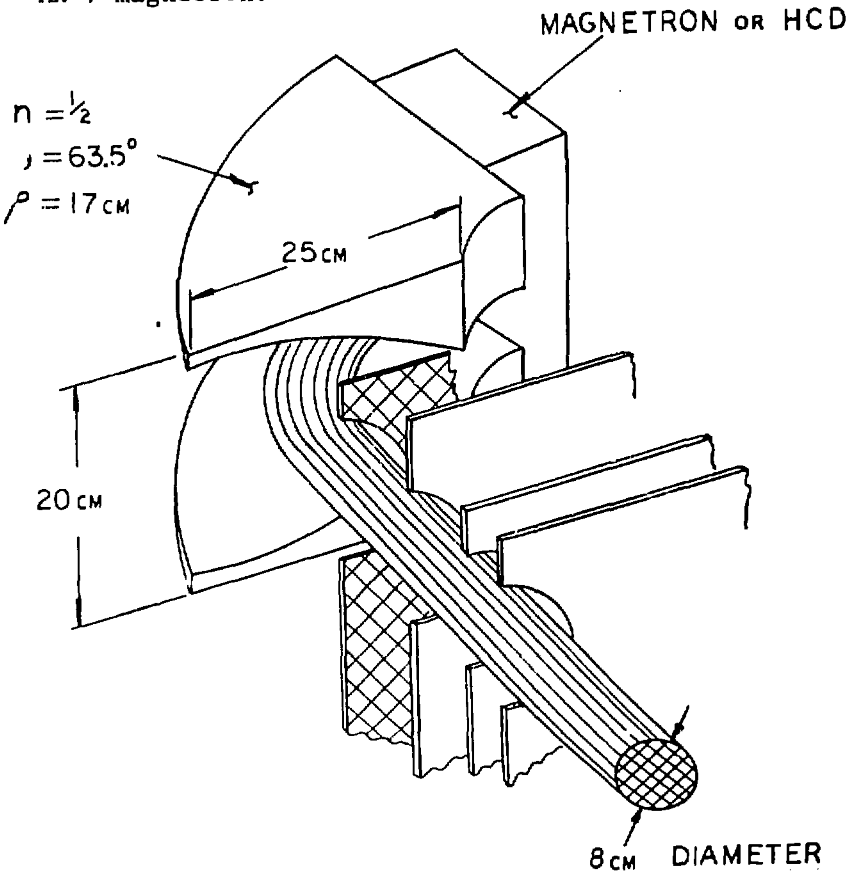


Fig. 3. Transport and acceleration of a 2A D^- beam from the magnetron.

The operating pressure of the source with HCD plasma is 10^{-4} to 10^{-3} Torr compared to about 0.1 Torr in the standard source so that the close coupled accelerator becomes attractive again. Figure 4 shows

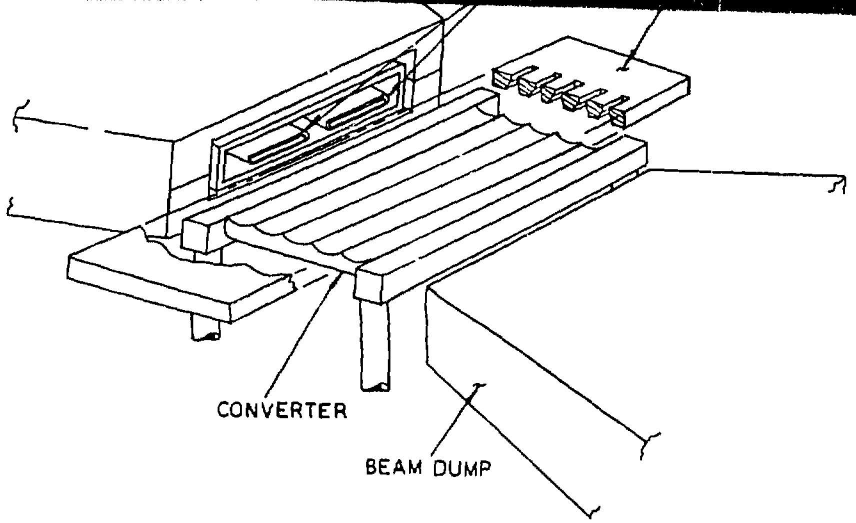
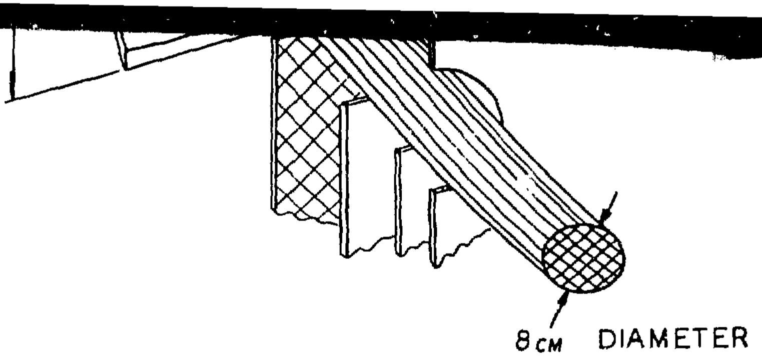


Fig. 2. Sketch of the HCD Experiment.

III. Beam Extraction, Transport and Acceleration

Properties of H^- beams extracted from pulsed magnetron sources have been extensively studied.[7] The beam is typically extracted from multiple slits (4-8 cm long, 0.5-1 mm wide) oriented perpendicularly to the source magnetic field. Sources with geometrical focusing of negative ions can be designed with a high H^- current density in the extraction slits (0.5-2 A/cm^2) and can, therefore, have a low anode wall transparency (10-20%). Emittance measurements of the extracted beam at 10-15 keV show a divergence of ± 75 mrad parallel to and ± 250 mrad perpendicular to the slits. Under optimum conditions, the extracted electron current can be as low as 50% of the H^- current; these electrons can be collected away from the H^- beam.

Although up to 1 A of H^- ions was accelerated to 130 keV in a close coupled high gradient accelerator,[8] the operation was not reliable due to a high local pressure. Experiments with the beam transport through a 90° bending magnet[7] have shown



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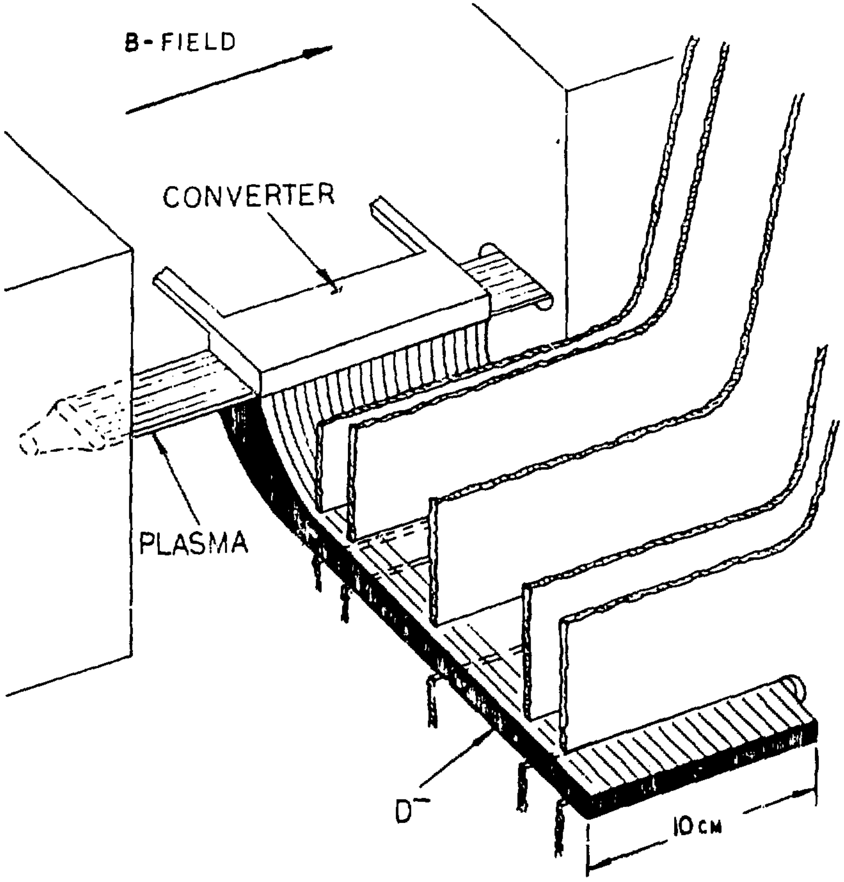


Fig. 4. Production and acceleration of a 2A D^- beam from an HCD based source.

a possible configuration, where negative ions are allowed to make 90° bend inside the source. In addition to the removal of unwanted particles from the beam there is one more advantage: H^- ions will be focused into the slit, thus reducing the gas flow even further. The system shown, with a 2 cm x 10 cm converter and an accelerator aperture of 1 cm x 10 cm, should deliver a 2 A, 200 keV D^- beam.

There are several other beam transport and acceleration options under consideration, particularly for beam energies above 400 keV. In a MEQALAC system[9] many individual beamlets may first be transported in an array of electrostatic quadrupoles, followed by beam bunching and then rf acceleration combined with electrostatic quadrupole focusing. There is no energy limit for this type of acceleration because dc voltages are eliminated. In the second scheme, the beam may again be first transported in an electrostatic quadrupole array, but the acceleration would be done in an accelerator, consisting of dc accelerating gaps alternating with electrostatic quadrupoles.[10] Finally, it is also possible to inject the 200 keV beam into a RFQ (radio frequency quadrupole) accelerator for further acceleration.

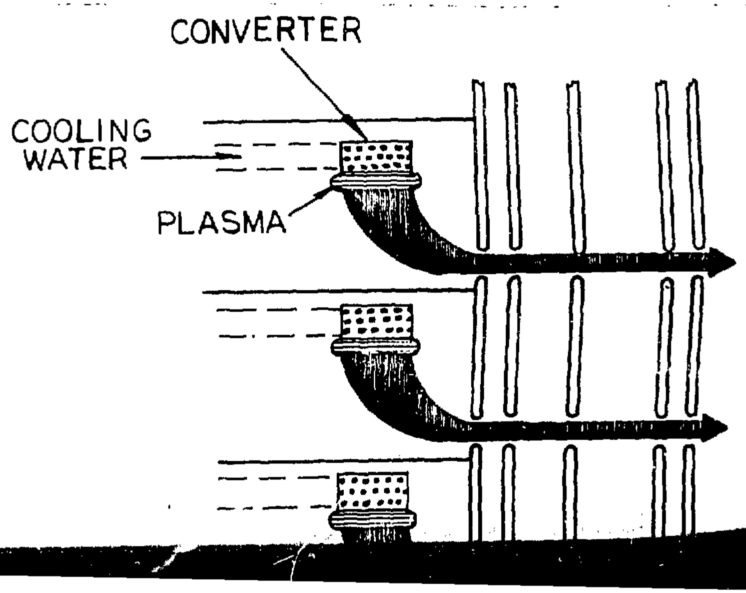
IV. Neutralization

In the range of energies and intensities that are of interest to fusion devices, there are three types of negative ion neutralizers[11] which can be considered: gas (or metal vapors), plasmas, and lasers (photodetachment). The theoretical limit of the neutralization efficiency, in the energy range above 50 keV nucleon, is about 60% for gas or metal vapor systems, about 80% for plasmas, and 100% for lasers. Although lasers offer an almost ideal system concerning the neutralization efficiency, this approach requires considerable development. As the second best, a concept for a plasma neutralizer has been developed at BNL. It is shown on Fig. 5 and it consists of a longitudinal solenoidal field where plasma is fed from a number of hollow cathode discharges, along the magnetic field lines. The neutralizer would operate at background pressures of the order of 10^{-4} Torr, which can be achieved by [illegible] pumping at the cathodes. Plasma density

system; taking into account losses during neutralization as well as different neutralization schemes, this beam should result in 1 to 1.5 MW of neutral particle power at the injection port of the fusion device.

If the magnetron is the chosen option for the source of negative ions, then five of 2A, 200 keV modules (as shown on Fig. 3) would be stacked and aimed to a common point at the injection port. Because of larger initial beam size (dilution of the extracted beam in the bending magnet), design of the neutralizer and of the system for charged component separation and dumping would differ from that in a HCD based beam line, but assuming that the divergence after acceleration is not larger than ± 1°, a final neutral flux density of some 20 mA/cm^2 equivalent should be achievable.

The other option, stacking of five HCD based modules as shown on Fig. 6, leads to a rather compact design (Fig. 7). Some tentative parameters of this beam line are given in Table I. If the final beam angle after acceleration is again ± 1°, then the beam size at the injection port would be about 20 cm x 30 cm; however, by aiming of individual beams this could be reduced and a neutral flux density of 24 mA/cm^2 equivalent would be achieved.



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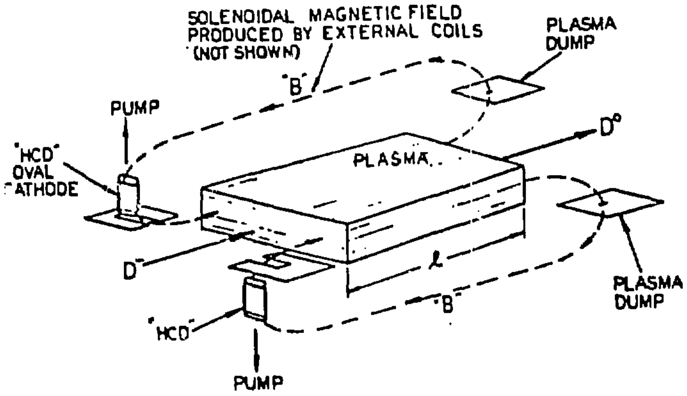

Fig. 5. HCD plasma neutralizer.

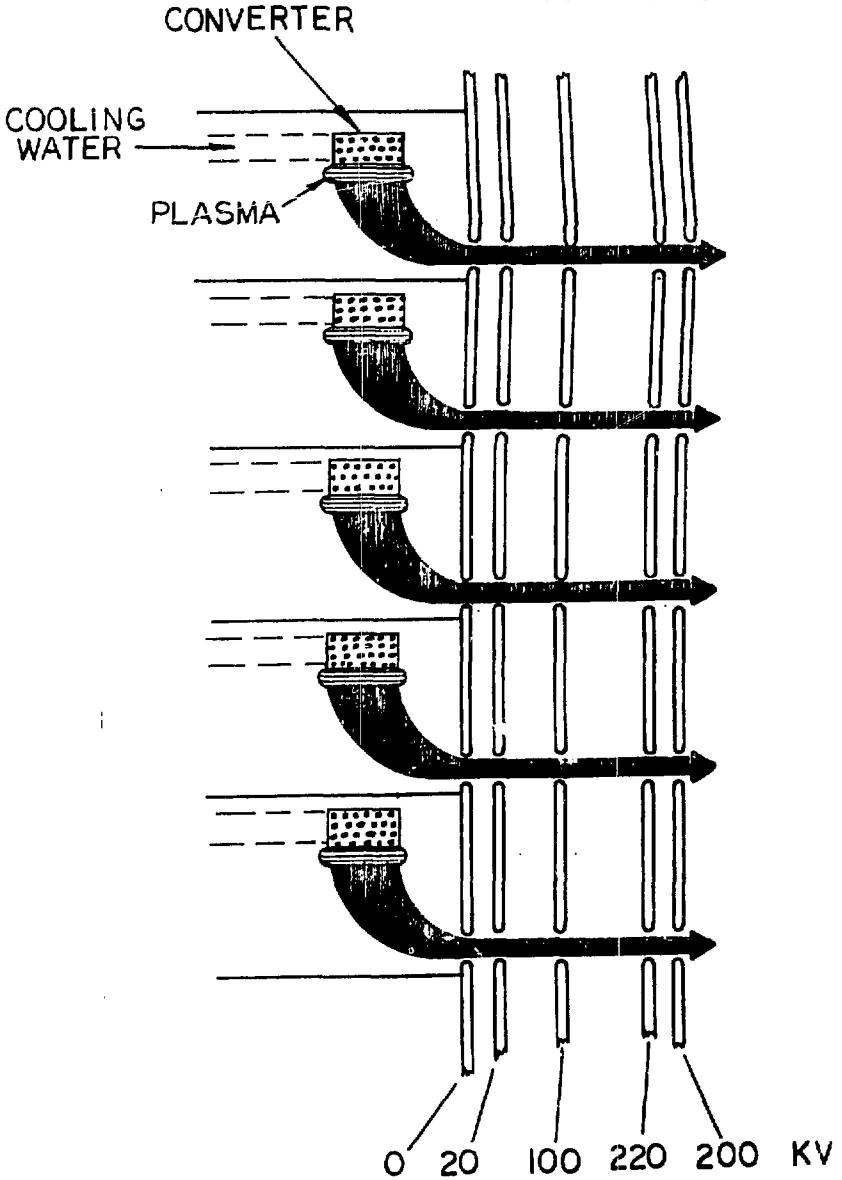

Fig. 6. A 10 A, 200 keV unit based on HCD modules.

V. Neutral Beam Systems

A 10 A, 200 keV D^- beam with acceptable divergence and efficiency is desired as proof-of-principle for a negative ion based neutral beam

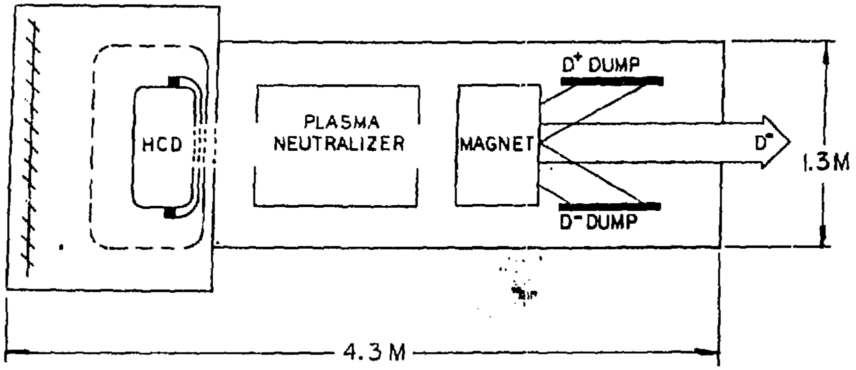

Fig. 7. Schematic of the 10 A, 200 keV D^- beam line.

Table 1

Tentative Parameters for a 1.6 MW D° Beam Line (10A, 200 keV D−)

HCD Source	
HC Current (total), Voltage	500A, 50V
Converter Current, (total), Voltage	100A, 100V
Pressure	10^{-4}–10^{-3} Torr
Source Pumping (total)	<200,000 1/sec
Gas Flow Through Extractors (total)	<1 T-1/sec
Accelerator	
Apertures	Five, 1cmx10 cm each
Current Density in Aperture	0.2A/cm^2
Voltage Gradient	<60 kV/cm
Length	~5 cm
HCD Plasma Neutralizer	
Neutralization Efficiency	80%
HC Current (total), Voltage	1000A, 50V
Plasma Density	4 x 10^{13}/cm^3
Length	30 cm
Gas Load	40 T-1/sec
Ion Deflection Magnet	
Field	1 kG
Length	50 cm
Gap	25 cm
Ion Beam Dumps	
Size	20 cm x 60 cm

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Apertures	Five, 1cmx10 cm each
Current Density in Aperture	0.2A/cm^2
Voltage Gradient	<60 kV/cm
Length	~5 cm
HCD Plasma Neutralizer	
Neutralization Efficiency	80%
HC Current (total), Voltage	1000A, 50V
Plasma Density	4 x 10^{13}/cm^3
Length	30 cm
Gas Load	40 T-1/sec
Ion Deflection Magnet	
Field	1 kG
Length	50 cm
Gap	25 cm
Ion Beam Dumps	
Size	20 cm x 60 cm
Power Density	170 Watts/cm^2
Power Per Dump	200 kW
Overall Beam Line	
Approximate Size	4 m x 1.5 m x 1.5 m
Overall Power Efficiency	50 - 60%
Final Neutral Current Density*	12-24 mA/cm^2
Final Neutral Power Density*	2.4-4.8 kW/cm^2

*3 meters from the accelerator, assuming $\theta = \pm 1°$, without and with aiming of beams

Neutralizaton of Negative Hydrogen Ions and Beams, BNL 51304, chapter on Neutralizers (1980).